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DETECTING CHANGES IN IRRIGATED AREA USING MULTI-TEMPORAL MODIS AND LAND SURFACE MODEL SURFACE TEMPERATURE WITHIN AMU DARYA DELTA

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The Amu Darya delta is an irrigation intensive region located in an arid drought-prone part of the Aral Sea basin. Due to irrigation which is characterized by high water application rates, the groundwater level is high and has resulted in secondary salinization. This coupled with the frequent droughts causes the irrigation area to constantly change for farmers to adapt to cropping environmental problems and the changing annual climate. However, obtaining an accurate report of the actual distribution of the irrigated area has proven to be difficult even to the local government and local agricultural institutes. This study aims to assess the potential of using Land Surface Temperature (LST) from MODIS and a Land Surface Model (LSM) to detect annual changes in irrigated area. 3 indices were developed using LST by MODIS and LSM based on the concept of heat capacity difference between water and soil. The LSM provides LST for ideal conditions while MODIS provides the actual LST. A combination of the two enables the elimination of external influence on LST such as rainfall and geological variations which may impact on the LST. A distributed map of all the 3 indices shows the potential of LST in detecting drought. The irrigation fraction during a drought year was observed to be lower as compared to that of a normal year. This was true especially further away from the water source due to water scarcity. In addition, a comparison of the sum of all the meshes in the study area for each of the 3 indices with the volume of water released from the Tuyamuyun reservoir shows a similar trend. Tuyamuyun is indicative of water availability in this drought-prone region, therefore, the indices developed can be used to indicate irrigation activity here.

Key Words: *Irrigation, MODIS, LSM, Drought, Amu Darya delta*

1. INTRODUCTION

In the past 50 years alone, the global area equipped for irrigation is estimated to have increased by more than 100 percent¹. Irrigated agriculture currently accounts for more than 70 percent of water withdrawal from rivers, lakes and groundwater aquifers making it the principal consumer of freshwater resources.

Many of the low rainfall regions such as the Middle East, Northern Africa, and Central Asia, have most of their exploitable water already withdrawn. It is estimated that approximately 80 to 90 percent of this water is going to agriculture, making rivers and aquifers depleted beyond any sustainable level².

In Central Asia, the Union of Soviet Socialist Republics (USSR) installed a massive scale irrigation

project within the Aral Sea basin. This led to a rapid expansion of irrigation from the late 19th century until the collapse of the USSR in 1991. As a result, the two main influent rivers to the Aral Sea; Amu Darya and Syr Darya suffered diminished inflow to their delta as more water became diverted for irrigation purposes (Furrow irrigation which is the main mode of irrigation in this basin is very water intensive). The amount of water reaching the sea significantly reduced, leading to its shrinking. The area of the sea is currently approximately 10 percent of its original area³⁾ consequentially plunging the region into a deep environmental crisis. This signifies one of the greatest environmental tragedies of the 20th century^{4,5)}. Irrigation has resulted in the salinization of soils rendering some lands unusable. FAO, (2016) reported that the assessment of salinization at the national level in Uzbekistan was found to be difficult and that very little information on the subject could be found⁶⁾. The actual irrigated area and crop type change annually not only due to the annual climatic variability but also as a strategy for farmers to adapt to irrigation-induced problems such as increasing salinization of soil.

Irrigation water is an important part of the hydrology cycle and has thus been included in recently developed hydrological models both at the basin and global scale^{7,8)}. These hydrological models are however based on the concept of fixed land use. The variability of irrigated area is an important component to be considered as it impacts the heat and water balance in the basin. Central Asia is a region where the land use changes dynamically. It is difficult to obtain an accurate estimation of the irrigated area because collecting data in a wide region is difficult especially in developing countries.

On a global scale, several attempts have been made to determine the spatial extent of irrigated land. The United States Geological Survey (USGS) Global Land Cover Characterization (GLCC) map is one such example. The Global Ecosystems legend identifies 4 irrigated classes. However, in addition to this dataset being static, irrigated areas are not isolated and are only part of a broader classification. Since the reviewed global land cover products are static, the land cover classification provided does not reflect land cover variability which may be caused by a reduction of the irrigated area especially during drought or dry years. In this case, the non-irrigated area may incorrectly be classified as irrigated.

In the regional scale, several studies have successfully used NDVI derived phenology and other climate and vegetation based indices to assess the spatial extent of irrigated areas. A study on crop mapping using NDVI showed that irrigated crops maintain higher NDVI than non-irrigated crops throughout

most of the growing season making it possible to discriminate the two⁹⁾. Additionally, Gumma et al., (2014) accurately captured the seasonal variability in rice crop spatial extent and area in Bangladesh with an R-squared value of more than 90 percent¹⁰⁾. However, some of the native plants in the Aral Sea basin, have long roots of between 10 to 30m and because the groundwater level in the delta is high, native plants flourish here making it difficult to separate irrigated area using NDVI.

Information on the spatial extent of irrigated areas found in statistical databases such as the Food and Agriculture Organization (FAO) AQUASTAT database is mentioned as ‘area equipped for irrigation’. This is the definition of irrigable land and not the actual irrigated area. Obtaining an accurate report of the actual distribution of irrigated area has proven to be a problem even to the local government and local agricultural institutes.

In this research, a combination of satellite analysis and Land Surface Modelling approach was performed to detect the irrigated area. A global dataset developed by Doll (2002) showing the percentage of area equipped for irrigation was used to identify the irrigable area in the basin¹¹⁾. The LST obtained from both MODIS and a LSM considering conditions with and without irrigation was used to detect the irrigation effect on heat balance in the basin. The objective of this study is to assess the annual changes in the irrigated area so as to facilitate an understanding of changing water demand through climatic variables.

2. TARGET BASIN

The Amu Darya delta shown in Fig. 1 below located in the Karakalpakstan republic Uzbekistan and partly in Turkmenistan is the target area for this study. Tuyamuyun dam located in the lower part of the delta has the primary purpose of providing water for irrigation. This delta is located in the driest part of Uzbekistan and is historically prone to droughts.

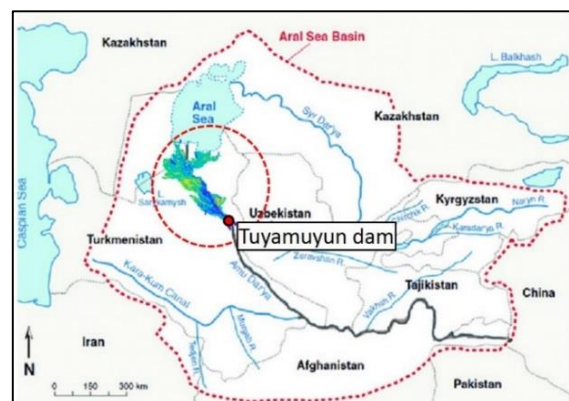


Fig. 1 Amu Darya delta in Aral Sea basin (Micklin, 2000)⁴⁾

In 2000, 2001 and 2008, drought caused numerous artificial reservoirs in Karakalpakstan to dry up, causing major water shortages not just for irrigation but also for drinking water¹²⁾. In 2000 and 2001 about 90% of the rice crop and 75% of the cotton crop were lost due to drought¹³⁾. This delta is also located in one of the most sensitive areas to climate change in terms of irrigation water demand in the Aral Sea Basin¹⁴⁾. Due to high water application rates, this region greatly suffers from secondary salinization as a result of rising water levels. Ibrakhimov et al., (2007) reported that in the Khorezm region located in the Amu Darya delta Uzbekistan, secondary soil salinization is annually adding 3.5 to 14 tons per hectare of salts on average¹⁵⁾.

3. METHODOLOGY

Since water has a higher heat capacity than soil, soil with high soil moisture does not immediately respond to temperature changes. Moreover, increased evapotranspiration as a result of the presence of irrigation water further reduces the LST in the day time. LST by the satellite represents the actual conditions on the ground while the LSM was used to provide the estimated ideal LST for both conditions with and without the influence of irrigation. The mesh was assumed to be fully irrigated when simulating irrigation conditions and fully non irrigated while simulating conditions without irrigation. Since MODIS provides the surface temperature for the actual conditions on the ground, when attempting to detect irrigation, it is sometimes impacted upon by precipitation. Additionally, effects on LST due to geological variability cannot be isolated. The purpose of the simulation of LST using the LSM is to remove the influence of this climatology and geological variability which results in temperature difference. LST is a difficult parameter to estimate and to validate in both satellite analysis and LSM because it is controlled by the atmospheric state and surface emissivity and requires the knowledge of many influencing parameters¹⁶⁾. Despite this, the simulation of LST by the model suffices in the isolation of the reduced temperature caused by irrigation and removing climatic and geological influence on temperature by considering climatological differences and difference in elevation. In this study, the actual LST by MODIS and the ideal LST by the LSM are used to isolate anthropogenic effects on LST.

(1) Utilized satellite data

MOD11A1 product which is a level 3 gridded product with a temporal resolution of 12 hours and a spatial resolution of 1km was used for LST data. LST

values at all grids are from single clear sky MODIS observations. MODIS collects daily observations from the study area at approximately 4 pm and 3 am local time. This study used MODIS data from 2001 when it was first available.

(2) SiBUC Land Surface Model

Simple Biosphere including Urban Canopy (SiBUC)¹⁷⁾ considers artificial water operation in irrigated land and water and heat balance on an urban area. The irrigation scheme in the green area sub-model caters for artificial water control. The basic concept of the irrigation scheme is to maintain soil moisture of the green area above minimum soil moisture defined for each growing stage of the crop. Irrigation scheme in this model was improved based on field investigation to consider local furrow irrigation rules in the basin¹⁸⁾.

For meteorological input, Japanese 55-year Reanalysis (JRA-55) was used to provide forcing data to the model. JRA-55 is a 55-year comprehensive global atmospheric reanalysis using a data assimilation system to provide a homogeneous climate dataset¹⁹⁾. Since all the data is provided at a temporal resolution of between 3 and 6 hours, hourly data was linearly interpolated and spatial interpolation was done using Inverse distance weighting (IDW). Global Satellite Mapping of Precipitation (GSMaP) version 6 data was used for precipitation data. This is a real-time radar derived dataset and it was used in order to isolate irrigation effect on soil moisture from that caused by rainfall.

Other datasets used in the simulation include GLCC and ECOCLIMAP (http://www.cnrn.meteo.fr/gmme/PROJETS/ECOCLIMAP/page_ecoclimap.htm) for land surface conditions such as land use, geological conditions, and leaf area index.

LST by the LSM was simulated using SiBUC LSM with a spatial resolution of 5km.

(3) Irrigation index

Based on this property, the following Eq.(1-3) below were used to develop LST based indices in an attempt to detect the irrigated area.

$$R_1 = \Delta ST_{SAT} - \Delta ST_{LSM_NI} \quad (1)$$

$$R_2 = \frac{ST_{SAT}^{day} - ST_{LSM_NI}^{day}}{ST_{LSM_IR}^{day} - ST_{LSM_NI}^{day}} \quad (2)$$

$$R_3 = \frac{ST_{SAT}^{day} - ST_{LSM_NI}^{day}}{AveST_{SAT}^{day} - AveST_{LSM_NI}^{day}} \quad (3)$$

where, R is irrigation index, ST is surface temperature, ΔST is surface temperature difference between day and night, $AveST$ is long term average of surface

temperature. And suffix of *SAT* means observed by satellite, *LSM_IR* and *LSM_NI* means simulated with full irrigation and without irrigation, respectively, and *day* means daytime.

Eq.(1) above was used to remove the climatic influences and the geological difference that may affect ΔLST in order to identify the irrigation effect in a mesh. Simulated LST by the LSM without considering irrigation is subtracted from MODIS LST representing the actual conditions observed in the study area to isolate the irrigation effect. Eq. (2) compares the irrigation effect observed by MODIS with the ideal simulated irrigation effect. Since this is the rate of the actual irrigation effect from the ideal irrigation effect, it would reflect the irrigation fraction in the mesh. Eq.(3) compares the irrigation effect observed by MODIS with the average simulated irrigation effect. This is used to detect a drought event by comparing the irrigation effect in a given year to an average year. The annual irrigation variability between a given year and an average year can therefore be compared.

(4) Statistical data used

The distribution of irrigated area in the study was retrieved from Doll (2002)⁽¹⁾, and the amount of water discharged to the study area was retrieved from the Tuyamuyun dam. Since this delta region is prone to drought, Tuyamuyun reservoir outflow should be representative of water availability in this region for irrigation.

4. RESULTS AND DISCUSSIONS

(1) Irrigation effect on surface temperature by LSM

Fig. 2 below shows monthly changes of LST in 2001 at 4 pm local time at a farm in Nukus in Karakalpakstan. This is based on the simulation by the LSM considering both irrigation effect in the entire mesh and without any irrigation in the same. The LST

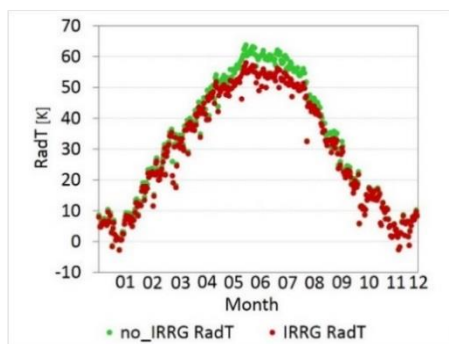


Fig. 2 Monthly changes of LST by LSM at 4 pm local time in Nukus

for both cases shows a similar trend at the start of the year with the LST considering irrigation dropping significantly during the irrigation period in the months of March to September before resuming a similar trend again. In this simulation, LST was physically calculated using the local climatology and geology, the results will then be compared with actual LST to detect irrigation.

(2) Detecting drought using LST

During the irrigation season, LST can be used to detect a drought year or a dry year. Such a year is characterized by scarcity of water leading to the abandonment of some irrigation land. A time series analysis of the day and night time LST difference using MODIS, in an irrigated mesh in Nukus, shows an approximate 4-degree difference in LST between an average year and a drought year as shown in Fig. 3 below. Due to some missing data as a result of cloud cover, a 30 point moving average was computed to show the LST trend during a drought year and an average year as seen by the green and red lines in Fig. 3 below.

A drop in temperature can be observed from June to October when irrigation for cotton is typically carried out and remains relatively unchanged until the end of summer where it drops sharply again. During the irrigation season, this day and night time difference of LST is approximately 20K in 2001 which is a drought year as opposed to 16K in 2017. Since MODIS has a much coarse spatial resolution than the farm-scale size in this region, the fraction of irrigated area is higher near the water source and reduces with an increase in distance. The irrigated area closer to the water source will have a lower LST than those further away.

Fig. 4 below shows the potential of the 3 indices to detect drought effect on irrigated area during the irrigation season. During a dry year, the irrigation fraction away from the water source is reduced due to water scarcity resulting in a higher LST. The indices were computed from a 10-day average of LST data.

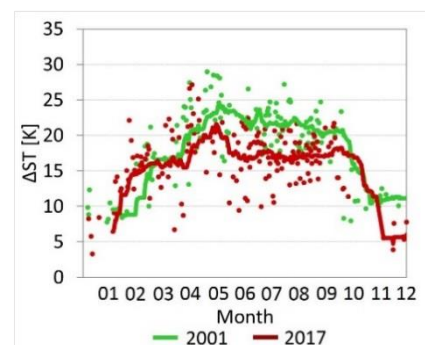


Fig. 3 Monthly changes of the difference of day and night time LST by MODIS at Nukus

Fig. 4 (a-c) shows a higher value for all the indices in the month of August 2001 especially in the northern part of the delta. In 2001, some areas in the north were severely affected by drought and could not be irrigated. This can be clearly viewed by the proposed LST indices. R_1 shows changes to the irrigated area due to anthropogenic effect which in this case, relates to the reduction of the irrigated area due to drought. R_2 seems to be directly related to the irrigation fraction and therefore has a much clear result on the impact of drought than R_1 and R_3 . It compares an ideal natural simulated effect of irrigation and the actual irrigation condition. R_3 seems least suitable of the 3 since it compares the actual condition to average changes which may include drought conditions in the past. Fig. 4 (d-f) shows an average year where the irrigation fraction is much larger as compared to 2001.

A comparison of the monthly sum of water volume released from the Tuyamuyun dam in August from 2001 to 2011 and the 3 indices also shows the ability

of the indices to detect irrigation in the meshes. The sum of each of the LST indices for all the meshes in the delta was compared to the total volume released from the Tuyamuyun dam. Fig. 5 below shows the results from this comparison. (a) shows the average sum of R_1 compared with the dam water volume released while (b and c) show the summation of R_2 and R_3 respectively compared with the water volume released from the dam. A similar trend can be seen between the water released and the indices. The higher the volume of water released for irrigation, the lower the value of the indices. Drought occurrence in 2001 and 2008 is also clearly indicated by these indices. However, since this analysis involved only the summation of indices, the result may be affected by meshes with extreme value. For further research, the irrigation fraction of all meshes needs to be analyzed more precisely and verified by local data to elucidate this. The month of August had the best results of 5 irrigated months observed (May to September).

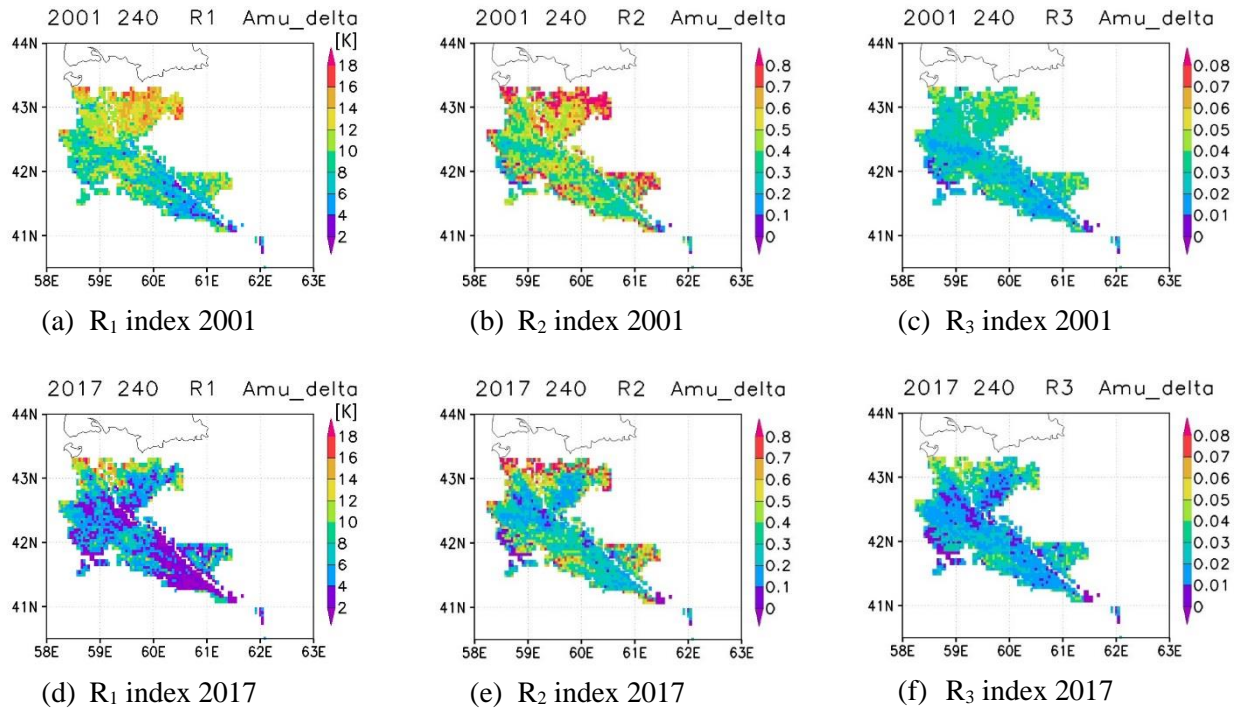


Fig. 4 Effect of drought on LST in the irrigated area

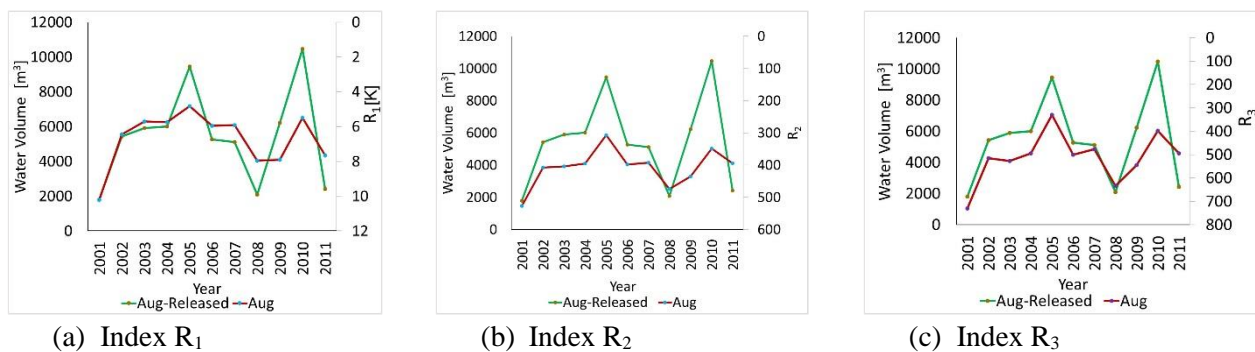


Fig. 5 Comparison of Tuyamuyun dam water volume released and the 3 indices

5. CONCLUSIONS

In this delta region, the area under irrigation in changing annual climatic conditions is unknown. This study uses LSM and MODIS LST to detect the irrigated area. Computation of LST by the LSM provided the ideal natural LST while actual LST was provided by MODIS. This was necessary to remove climatic and geological influence on LST to identify anthropogenic influence which might affect the temperature. Tuyamuyun dam water volume data provided a representation of water availability in this delta region which is prone to drought.

Due to the difference in heat capacity between water and soil, it was expected that soil with high moisture content will not respond immediately to temperature changes. Therefore, 3 indices were developed to detect the irrigated area.

The results show the potential of the indices to detect irrigated area and the effect of drought on this area. Irrigation fraction during a drought year was observed to be lower as compared to that of a normal year especially further away from the water source due to water scarcity. This was further confirmed by the summation of values for each index for all the meshes which were compared to the released volume from the Tuyamuyun dam.

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